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INVESTIGATION OF A LARGE WINGED FIRST STAGE OF A VTO REUSABLE ORBITAL LAUNCH VEHICLE FROM MACH 2.3 TO 6.0

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INVESTIGATION OF A LARGE WINGED FIRST STAGE OF A VTO REUSABLE ORBITAL LAUNCH VEHICLE FROM MACH 2.3 TO 6.0*

By P. Kenneth Pierpont
Langley Research Center

SUMMARY

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An exploratory investigation has been made of a preliminary design of the reusable first stage of a large-payload vertical-take-off launch vehicle at Mach numbers from 2.3 to 6.0. Angle-of-attack ranges were from -4° to 56°. Data were generally obtained at sideslip angles of 0° and 5°. Test Reynolds numbers ranged from 0.6×10^{6} to 2.0×10^{6} per foot.

The results indicated that the wing-body-tail configuration was generally unstable longitudinally, laterally, and directionally for the estimated center-of-gravity location. Hypersonic maximum lift-drag ratios of 1.6 to 1.2 were estimated at Mach numbers from 3.0 to 6.0, respectively. Conf

INTRODUCTION

The aerodynamic feasibility of providing for the recovery and reuse of the first stage of vertical-take-off two-stage-to-orbit launch vehicles by means of an attachable fixed-wing recovery system is under investigation at the Langley Research Center. References 1 and 2 report transonic and hypersonic characteristics of a fixed-wing first stage having a high-fineness-ratio rocket booster. Reference 3 reports transonic and some low-supersonic aerodynamic characteristics for exploratory wing-body-tail configurations having a low-fineness-ratio first-stage rocket booster.

The purpose of the present investigation was to extend the range of the aerodynamic information to hypersonic speeds for one of the reusable booster configurations employed in reference 3. Most of the investigation was conducted in the 2-foot hypersonic facility at the Langley Research Center; however, a selected configuration was also tested in the Langley Unitary Plan wind tunnel. The Mach number ranges were 3.0 to 6.0 and 2.3 to 4.65, respectively, for the two facilities. Data to derive static longitudinal and lateral stability characteristics were obtained over an angle-of-attack range at 0° and 5° sideslip. The Reynolds number varied from 0.6×10^{6} to 2.0×10^{6} per foot.

*Title, Unclassified.

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SYMBOLS

The aerodynamic data are reduced to standard coefficient form. Data for the basic booster and all lateral directional data are referred to body axes. The longitudinal data for the reusable booster are referred to the stability axes. The moment reference for all data was selected to be 1.25 body diameters forward of the model base. All coefficients are referred to the body-base area and the body diameter:

C_N normal-force coefficient, $\frac{\text{Normal force}}{q_\infty S_{ref}}$

C_A axial-force coefficient, $\frac{\text{Total axial force}}{q_\infty S_{ref}}$

C_L lift coefficient, $\frac{\text{Lift}}{q_\infty S_{ref}}$

C_D drag coefficient, $\frac{\text{Total drag}}{q_\infty S_{ref}}$

C_m pitching-moment coefficient, $\frac{\text{Pitching moment}}{q_\infty S_{ref} D}$

C_l rolling-moment coefficient, $\frac{\text{Rolling moment}}{q_\infty S_{ref} D}$

C_n yawing-moment coefficient, $\frac{\text{Yawing moment}}{q_\infty S_{ref} D}$

C_Y side-force coefficient, $\frac{\text{Side force}}{q_\infty S_{ref}}$

C_{L_α} lift-curve slope, $\frac{\partial C_L}{\partial \alpha}$, per deg

$C_{m_{C_L}}$ longitudinal-stability parameter (referred to stability axes), $\frac{\partial C_m}{\partial C_L}$ at $C_L = 0$

C_{n_β} directional-stability parameter, $\frac{\Delta C_n}{\Delta \beta}$, per deg at $\alpha = 0^\circ$

C_{l_β} effective-dihedral parameter, $\frac{\Delta C_l}{\Delta \beta}$, per deg at $\alpha = 0^\circ$

C_{Y_β} side-force parameter, $\frac{\Delta C_Y}{\Delta \beta}$, per deg at $\alpha = 0^\circ$

L/D lift-to-drag ratio, $\frac{C_L}{C_D}$

c local chord, ft

$\bar{c}$ mean aerodynamic chord of exposed wing, ft (0.303 ft)

D body diameter, ft (0.132 ft)

M free-stream Mach number

q_∞ free-stream dynamic pressure, lb/ft^2

S_{ref} model reference area, $\frac{\pi D^2}{4}$, sq ft (0.0136 sq ft)

t local thickness, ft

x_{cp} distance from body-base reference station to center of pressure, ft

α angle of attack, deg

β angle of sideslip, deg

Subscripts:

o conditions at zero angle of attack or zero lift

max maximum

DESCRIPTION OF MODELS

The models employed in this investigation consisted of a basic rocket booster to which was added an assembly, consisting of the wing and vertical tails, to make up the reusable booster. General model arrangement and component details are shown in figure 1 and photographs, in figure 2. The model employed in the Langley Unitary Plan wind tunnel was identical to the model employed in reference 3, whereas the model used in the 2-foot hypersonic facility at the Langley Research Center was one-half of the scale of this model; therefore, only the dimensions for the smaller model are given herein.

Basic Booster

The basic booster consisted of the cylindrical body 4.0 diameters long with a hemisphere forebody and rocket-engine shrouds at the model base as shown in figure 1. The shrouds (fig. 1(b)) were essentially 15° half-cones having a length of about 0.79D, and they were spaced 90° apart around the base, beginning at the top of the model.

Reusable Booster

The reusable booster consisted of the basic rocket booster with the addition of a trapezoidal wing and vertical tails. The trapezoidal wing was mounted on the basic booster so that the wing-chord plane was tangent to the body diameter at the plane of symmetry and so that the $0.25\bar{c}$ station of the exposed planform of the single-tail configuration coincided with the estimated center of gravity, which was 1.25D forward of the model base. The wing had 65° leading-edge sweep, a taper ratio of 0.20 (exposed), an area of $7.5D^2$ (exposed), and zero dihedral. The total wing-span-to-body-diameter ratio was 4.75, and the exposed panel aspect ratio was 1.87. The airfoil consisted of a symmetrical 10-percent-thick circular-arc section in the streamwise direction. The leading-edge radius was $t_{max}/6$, and the trailing edge was blunt with a thickness of $t_{max}/3$. Details of the wing are shown in figure 1(b). Vertical-slab side fairings with no radius at the wing juncture provided the fairing between the wing and the body. At the leading edge of the wing, the side fairings were faired by hand to the body to form a gentle upwardly sloped lower surface as shown in figure 2. The nacelles shown in the photographs are representative of one possible flyback engine installation but were removed for this investigation.

The planform for each of the single vertical tails corresponded to the outer 20 percent of the wing-panel area. The vertical tails were mounted outboard on each wing panel such that the root chord of the tail coincided with the local wing chord; hence, 20 percent of the wing area was outboard of the vertical tails. A toe-in angle of 3°, obtained by rotating the vertical tail about its midchord, was provided because of anticipated directional-stability problems; no cant was employed. For some of the tests, a double vertical-tail arrangement was used. This arrangement was obtained by considering the outer wing panel to have been folded down to a position coplanar with the upper vertical tail to double the vertical-tail area and to eliminate the area outboard of the vertical tails in order to decrease the expected large hypersonic longitudinal stability.

APPARATUS AND TESTS

Most of the tests were conducted in the 2-foot hypersonic facility at the Langley Research Center, described in reference 4, at Mach numbers of 3.0, 4.5, and 6.0 and angles of attack from about -4° to about 13° and generally sideslip angles of 0° and 5°. A selected configuration of the larger model, one of the models used in reference 3, was tested in the Langley Unitary Plan wind tunnel, described in reference 5, at Mach numbers of 2.3, 2.95, and 4.65 at angles of attack from about -2° to 56° and at 0° and 5° sideslip. For the hypersonic facility tests, the model had no artificial transition strips, and the flow over the model was considered to be essentially laminar at low angles of attack. For the tests in the Unitary Plan wind tunnel, artificial transition, consisting of a 0.1-inch-wide strip of No. 80 carborundum grains, was installed at the juncture of the nose and the body and at the 0.10c station on both surfaces of the wings and vertical tails. Reference 6 and experience in the Unitary Plan wind tunnel served as a guide in the selection of the grit size. For these tests, turbulent flow existed over most of the model at $M = 2.3$ and 2.95, but it is questionable that turbulent flow was obtained at $M = 4.65$. The test Reynolds number per foot varied from 0.6×10^6 to 1.2×10^6 in the hypersonic facility and was held approximately constant at 2.0×10^6 in the Unitary Plan wind tunnel.

Static aerodynamic force and moment data were measured with a six-component internally mounted strain-gage balance. Angles of attack and sideslip were corrected for balance and sting deflections under aerodynamic load. All drag data are presented with no base-pressure corrections applied. All forces and moments are reduced to coefficient form and are referred to the area of the base of the cylindrical body and its diameter in order that comparisons may be readily made. The moment-reference station was located 1.25D forward of the model base. (See fig. 1.)

RESULTS AND DISCUSSION

The investigation was divided into two parts. The first part consisted of determining the aerodynamic characteristics of the basic expendable booster configuration (body alone), and the second part consisted of obtaining the longitudinal and some lateral aerodynamic characteristics of the booster with the added assembly of the wings and tails to make up the reusable booster. Longitudinal data referred to the body axes for the expendable booster are given in figure 3. Longitudinal data, referred to the stability axes, for the reusable booster are given in figures 4 to 6; the lateral data, referred to the body axes, are given in figures 7 to 9. A summary of the more important aerodynamic parameters is shown in figure 10 for both the expendable and the reusable boosters. All force and moment data are referred to the body-base area and diameter; the assumed center of gravity was located 1.25 body diameters forward of the body base.

Basic Booster

The data shown in figure 3 were used to evaluate the effects on the aerodynamic characteristics of the addition of the 15° conical-shaped engine shrouds to the basic booster. These shrouds are considered to be required since the rocket-engine nozzles would extend outside the body-base diameter (see ref. 3) and would require protection from large aerodynamic forces during launch. The data indicate that the installation of shrouds caused generally insignificant changes in the normal-force-curve slope, increases in axial force, and stabilizing increments in the pitching-moment curves. The increment in axial-force coefficient, for example, 0.11 at $M = 3.0$, is considered to be primarily associated with the large increase in the base area - about 47 percent. The decreasing trend of the increment with increasing Mach number resulted essentially from a reduction in the absolute value of the base-pressure coefficient.

Reusable Booster

Longitudinal aerodynamic characteristics.- The effects of rocket-engine shrouds and vertical tails on the longitudinal aerodynamic characteristics of the reusable booster are shown in figures 4 and 5 to consist principally of changes in the longitudinal stability. Figure 4 shows that positive longitudinal stability was measured at $M = 3.0$ but that appreciable deterioration with increasing Mach number occurred for the vertical-tail-off data. When the double vertical tails were installed (see fig. 4), a large destabilizing increment resulted, principally caused by the decreased lifting surface area of the wing rearward of the moment-reference center - the wing tip was folded down to form the lower fin. The high angle-of-attack data of figure 6 for this same configuration shows that the pitching-moment curves are approximately linear to nearly maximum lift coefficients. Comparison of figure 4 (for tails off) and figure 5 (for single tails) shows that the installation of this tail configuration did not appreciably alter the longitudinal stability. Figure 5 shows that the primary influence of the shrouds was to shift or displace the pitching-moment curves in a positive direction. This effect may have been caused by the positive pressure field created by the shrouds acting on the rear portion of the wing. Figure 10 summarizes the longitudinal stability parameters of both the basic and the reusable boosters with single vertical tails in terms of $C_{m_{C_L}}$ as a function of Mach number and illustrates the large contribution of the wing. It is evident that, as was found in reference 3, at subsonic and transonic speeds, a rearward shift of the wing, possibly coupled with a change in planform, will be needed to achieve positive longitudinal stability at supersonic and hypersonic speeds.

Inasmuch as the single-vertical-tail configuration would not involve variable geometry it was selected to extrapolate the data to estimate maximum L/D. Drag-due-to-lift factors were calculated from the available test data and were applied to estimate $(L/D)_{max}$. The results are shown in figure 10 and indicate that the maximum L/D ratios would decrease from about 1.6 at $M = 3.0$ to 1.2 at $M = 6.0$. These values are relatively below those which would be expected for aerodynamically efficient wing-body configurations having the same volume and wing area; these low L/D values are caused in large measure by the large drag forces associated with the hemispheric nose, large leading-edge radius, and the unusually large base areas involved. When the drag contributions of these components are considered, the low $(L/D)_{max}$ values indicated were not unexpected.

Lateral aerodynamic characteristics.- The lateral aerodynamic data of figures 7 to 9 make it obvious that some geometric dihedral or its equivalent will have to be incorporated to provide positive lateral stability in the low angle-of-attack range. However, moving the vertical tails to the wing tip and employing outboard cant, as was done for one configuration in reference 3, may prove adequate. At high angles of attack, the data for the double-tail configuration (fig. 9) show that some positive effective dihedral was obtained at the two lower Mach numbers but that at $M = 4.65$ no positive-dihedral effect is shown even up to angles of attack of 56°.

[redacted]

The data of figures 7 to 9 show that essentially no directional stability was obtained at hypersonic speeds, even for the double-tail configurations. For the single-tail configuration, the longitudinal-stability data indicated a need for more lifting surface area rearward of the moment-reference center. The potential for substantially improving the directional stability for this configuration exists if the fin can be relocated at the wing tip. Estimates made from the present data indicate that, coupled with an increase in vertical-tail area of about 25 percent, an increase in vertical-tail effectiveness of more than twice that presently shown can be obtained. This increase will be approximately enough to give some directional stability in the supersonic-speed range of this investigation. The problem of obtaining directional stability at high angles of attack can be expected to be relieved by canting the vertical tails outboard if they are relocated at the wing tip. The high angle-of-attack data obtained for the double-tail configuration (fig. 9) indicate that at a Mach number of 4.65 the directional instability has been reduced, although this reduction occurs at much greater angles of attack than those required to obtain $(L/D)_{max}$. The data of figure 8 show that the lateral directional characteristics were approximately linear over the range of sideslip angles from -8 to 4. Figure 10 summarizes the lateral directional stability for the single-tail configuration at 0° angle of attack and shows that considerable improvement in both C_{l_β} and C_{n_β} are required.

CONCLUDING REMARKS

An investigation has been conducted to determine some of the aerodynamic characteristics of bodies and wing-body-tail configurations representative of the low-fineness-ratio first stage of a large payload vertical-take-off reusable launch vehicle. Test data were obtained at Mach numbers from $M = 2.3$ to 6.0 over an angle-of-attack range from -4° to 56° and at sideslip angles of 0° and 5°. Test Reynolds number ranged from 0.6×10^6 to 2.0×10^6. The following remarks are considered appropriate from the test results:

1. Longitudinal, lateral, and directional instabilities were measured for most conditions for the reusable booster.

2. Hypersonic maximum lift-to-drag ratios were estimated to vary from about 1.6 to 1.2 at $M = 3.0$ and 6.0, respectively, for the reusable booster.

3. Installation of rocket-engine shrouds caused important changes in stability of the basic booster but generally resulted only in a shift in level of the pitching-moment curves for the reusable booster.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 25, 1965.

[redacted]

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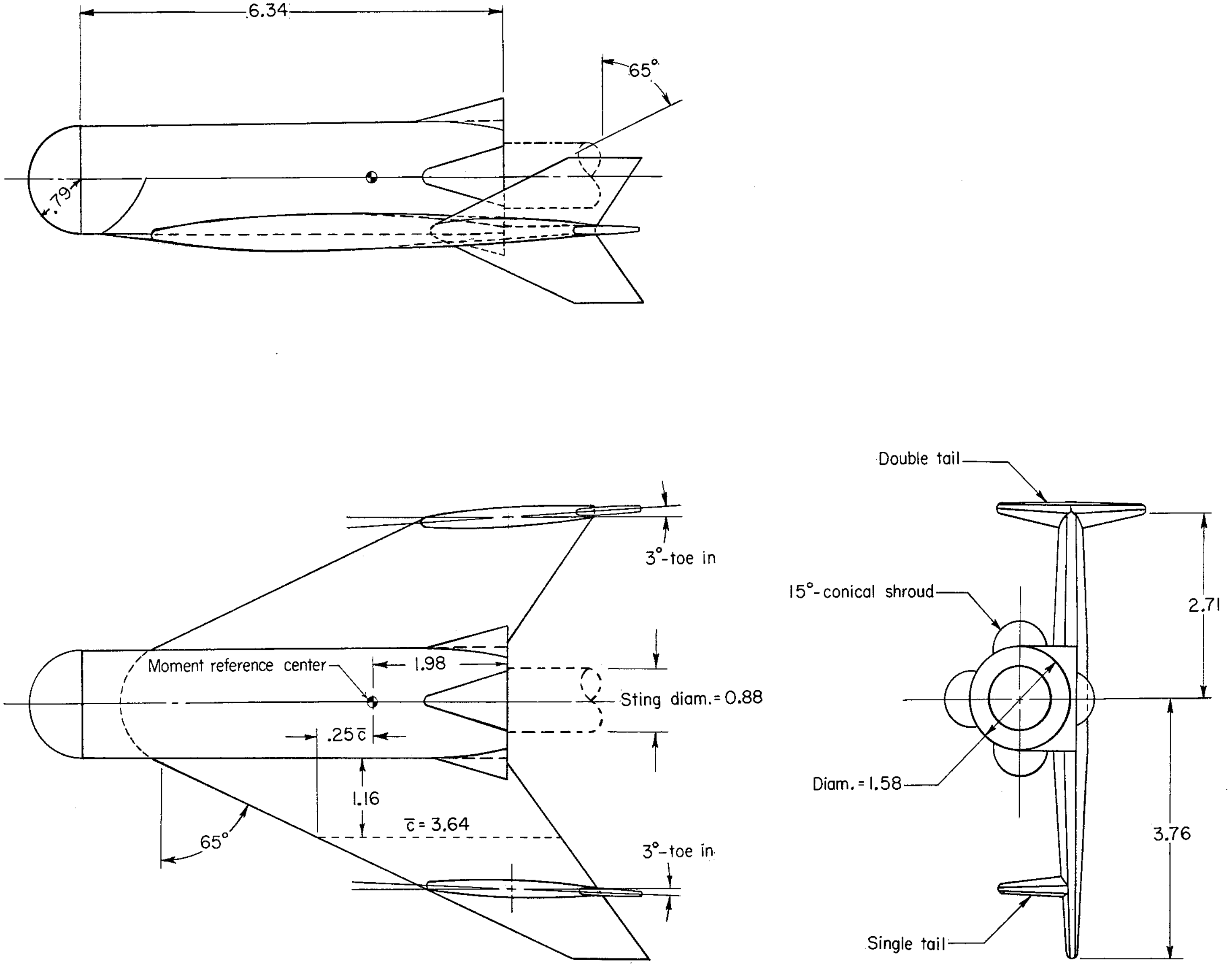
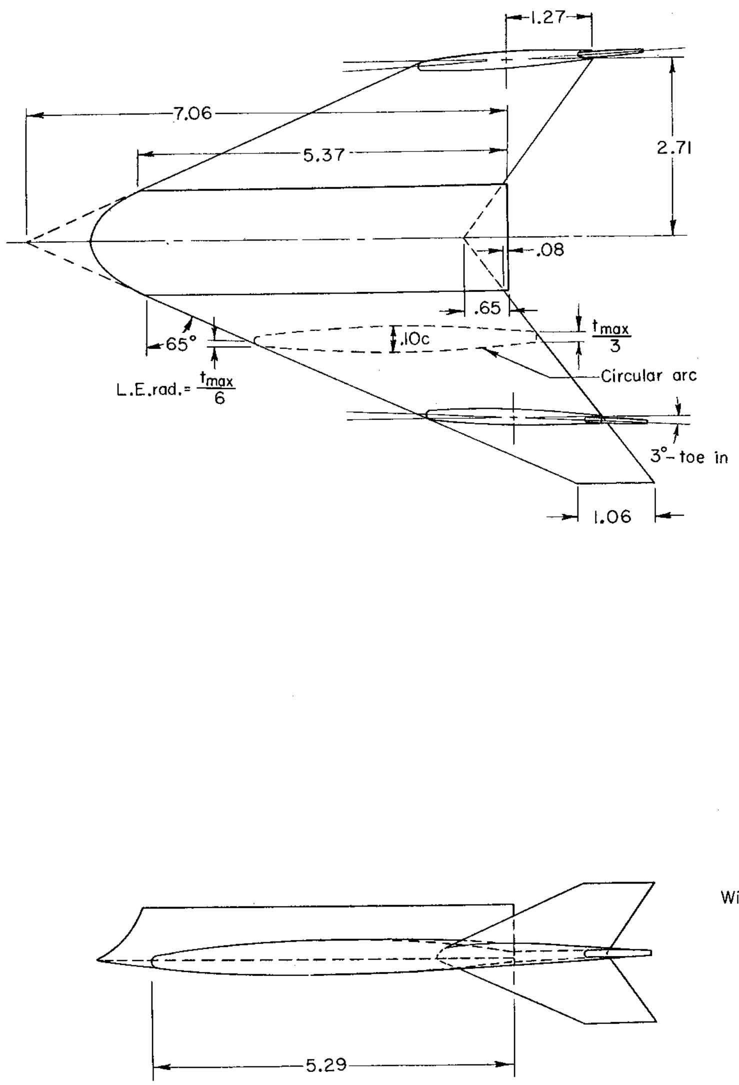
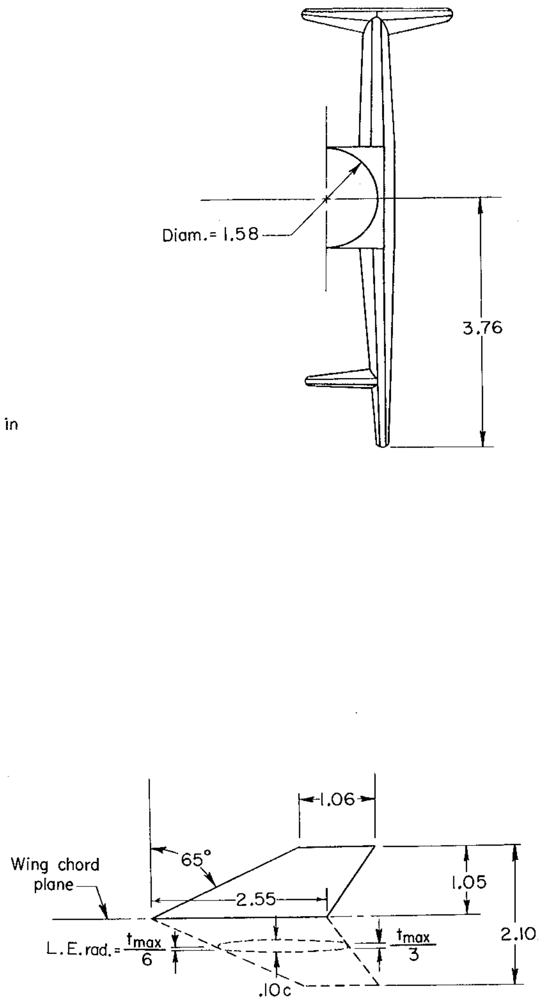


(a) General arrangement.

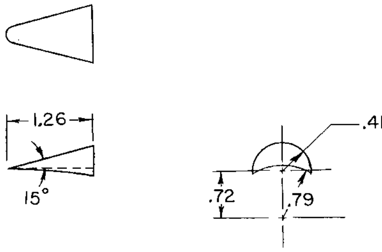
Figure 1.- Configuration and details of 65°-swept trapezoidal winged first-stage reusable booster employed in 2-foot hypersonic facility at the Langley Research Center. (All dimensions in inches.)



Wing



Vertical tail



Conical shroud

(b) Component details.

Figure 1.- Concluded.

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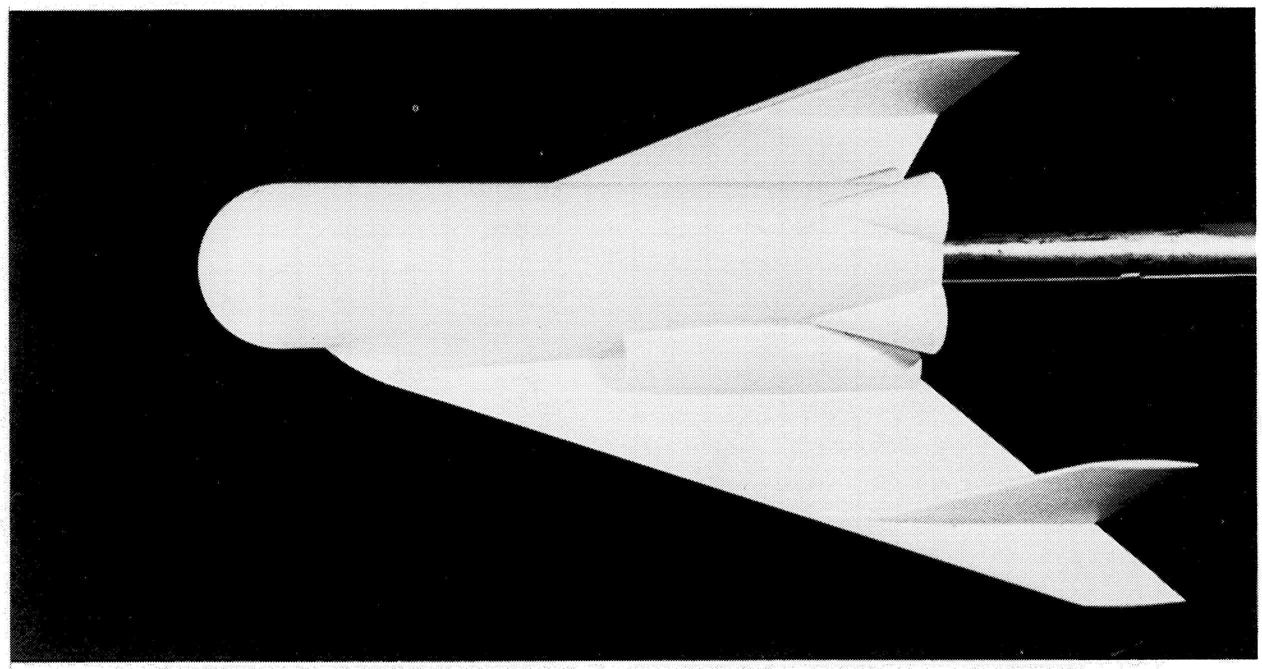
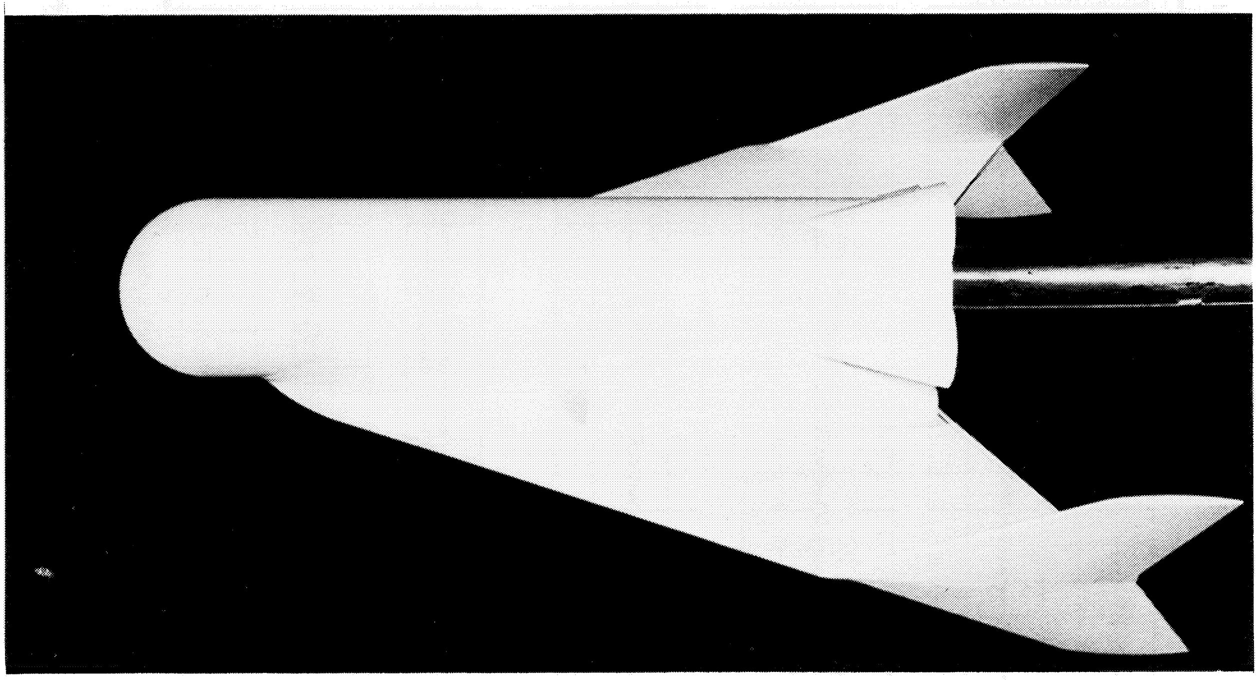


(a) Single-vertical tails. L-63-8568



(b) Double-vertical tails. L-63-8570

Figure 2.- Photographs of reusable booster.

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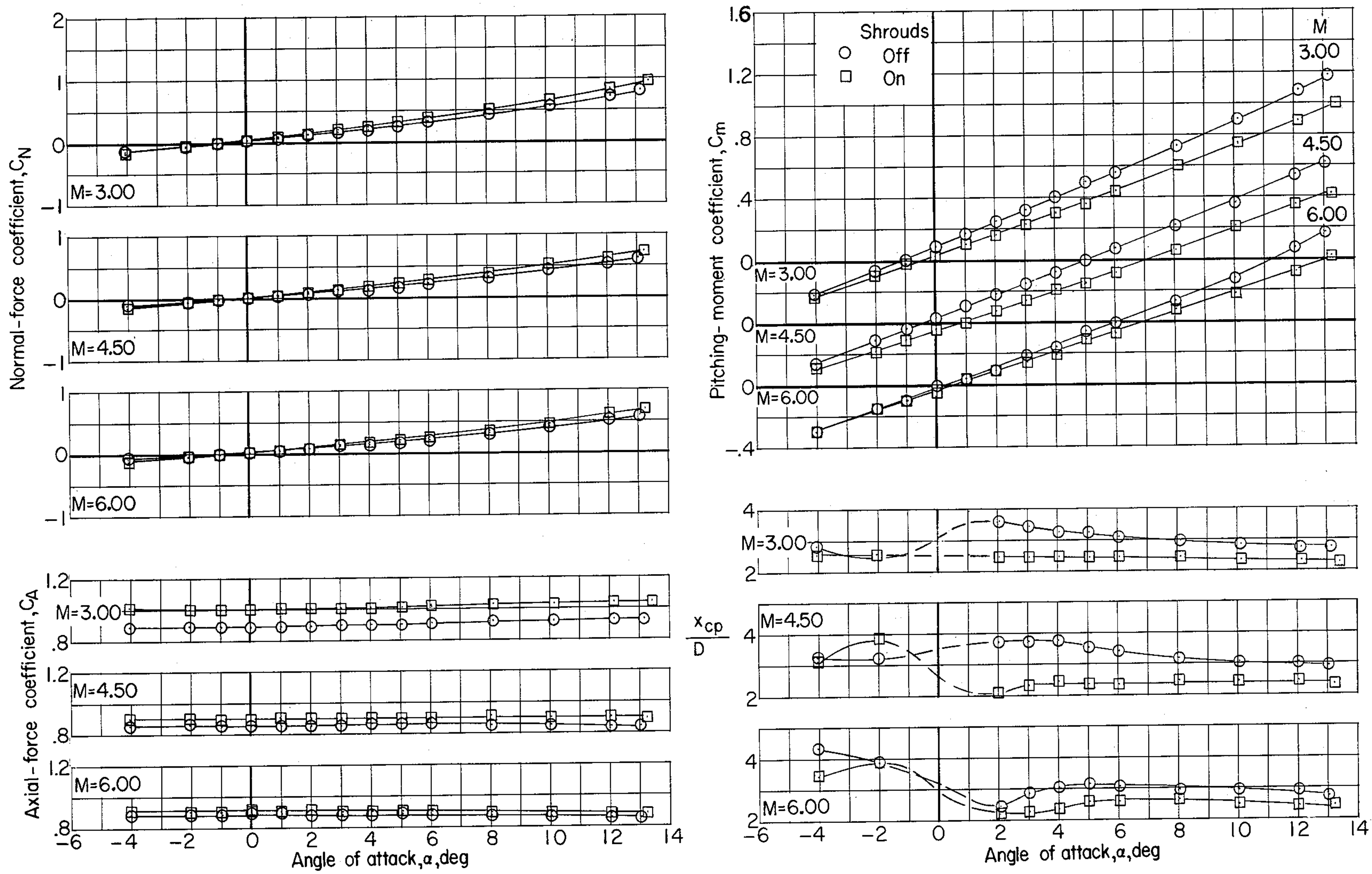

Figure 3.- Longitudinal aerodynamic characteristics of basic booster without and with rocket engine shrouds. $\beta = 0^{o}$.

[redacted]

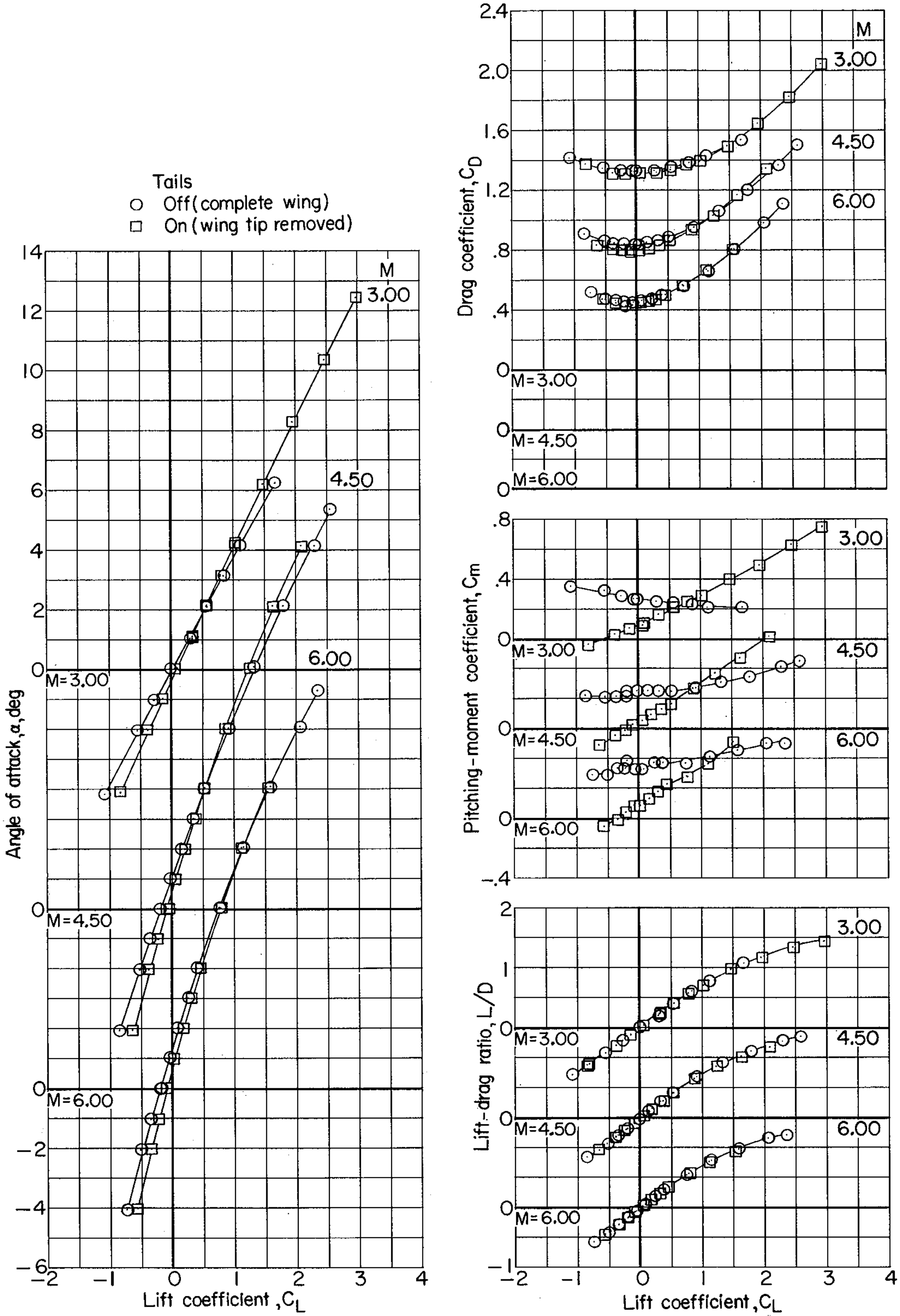

Figure 4.- Longitudinal aerodynamic characteristics of reusable booster without and with double-vertical tails. Shrouds on; $\beta = 0^{o}$.

[redacted]

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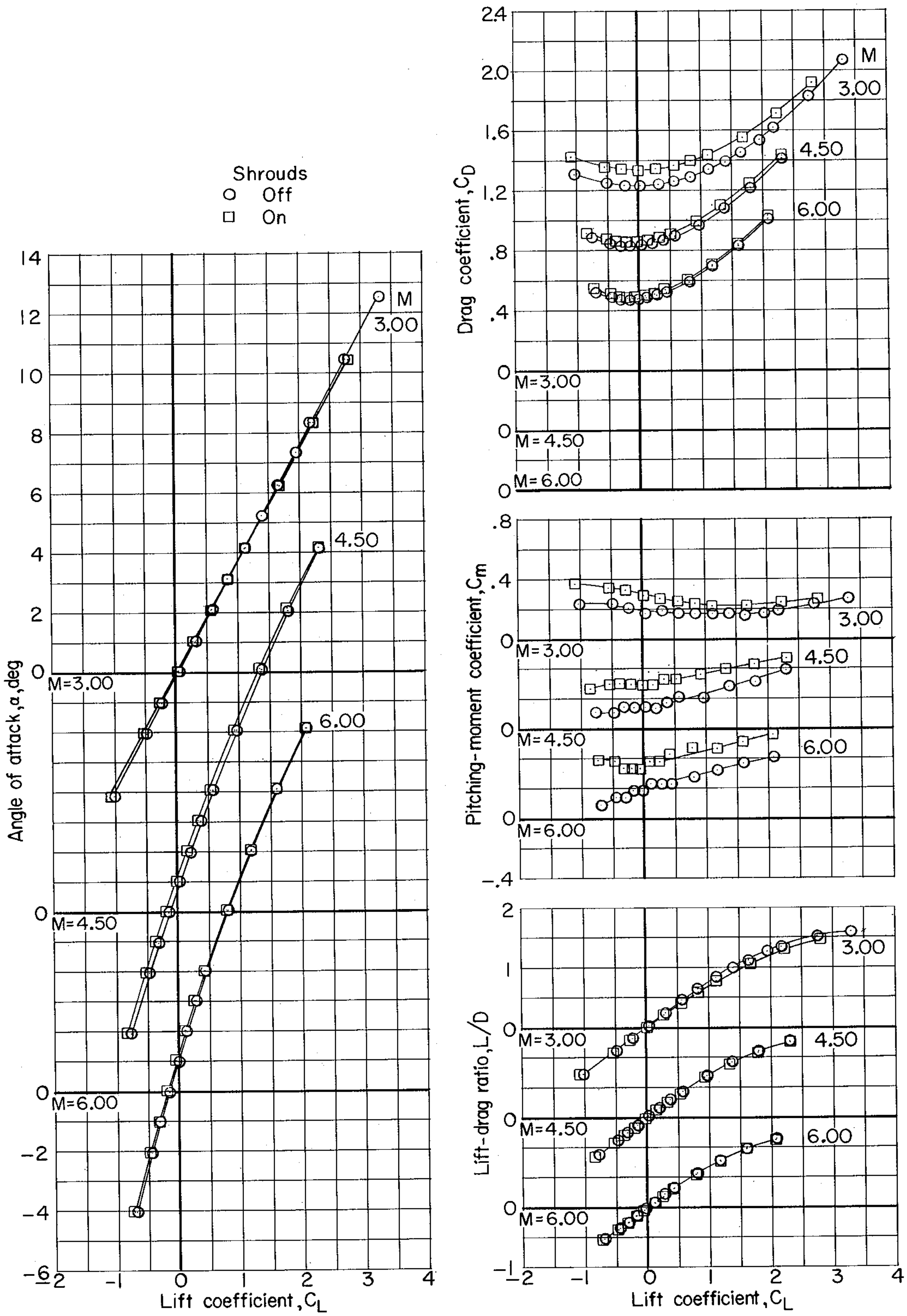

Figure 5.- Longitudinal aerodynamic characteristics of reusable booster with single-vertical tails showing effects of rocket-engine shrouds. $\beta = 0^{\circ}$.

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[redacted]

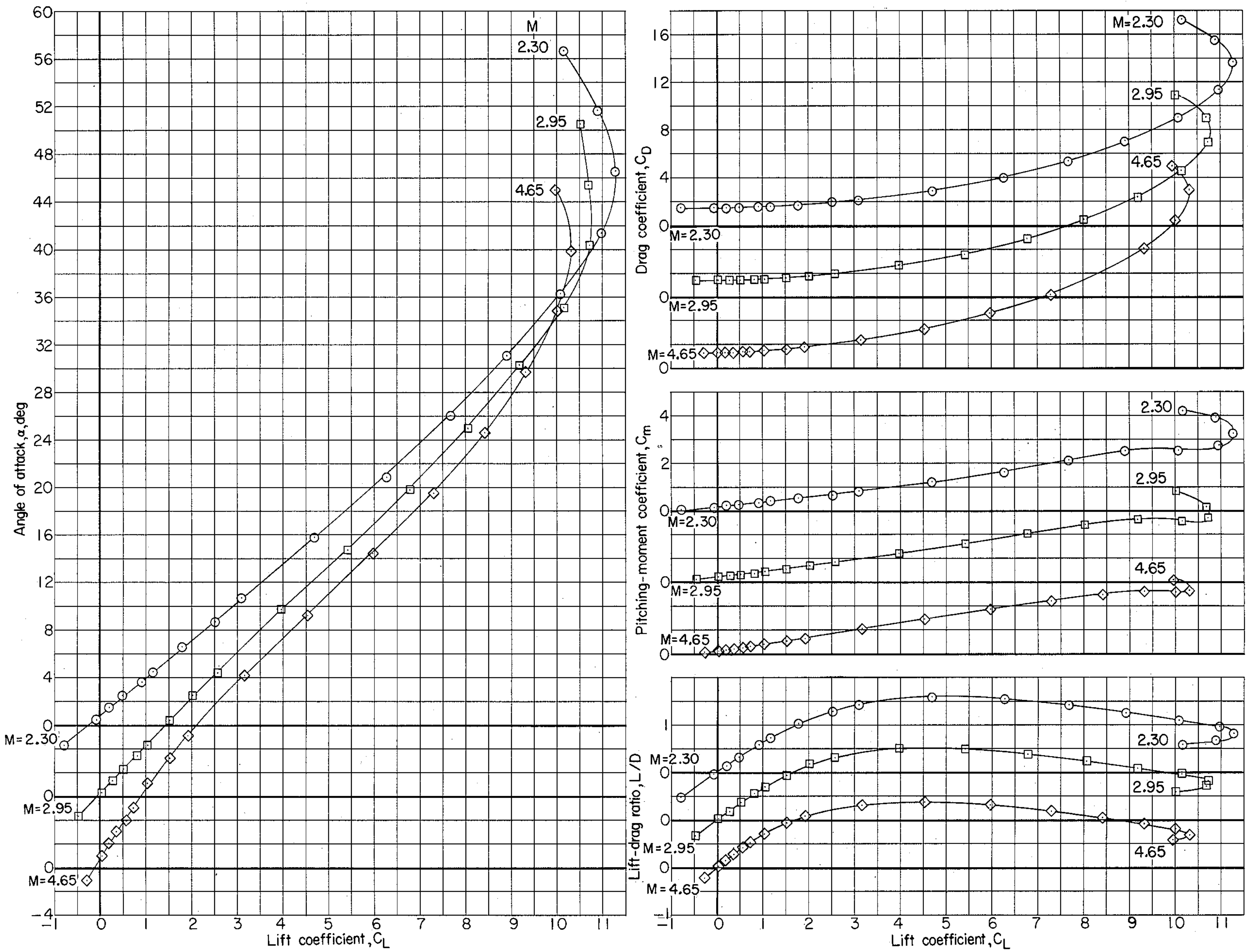

Figure 6.- Longitudinal aerodynamic characteristics at high angles of attack of reusable booster with double-vertical tails. Shrouds on; $\beta = 0^{o}$.

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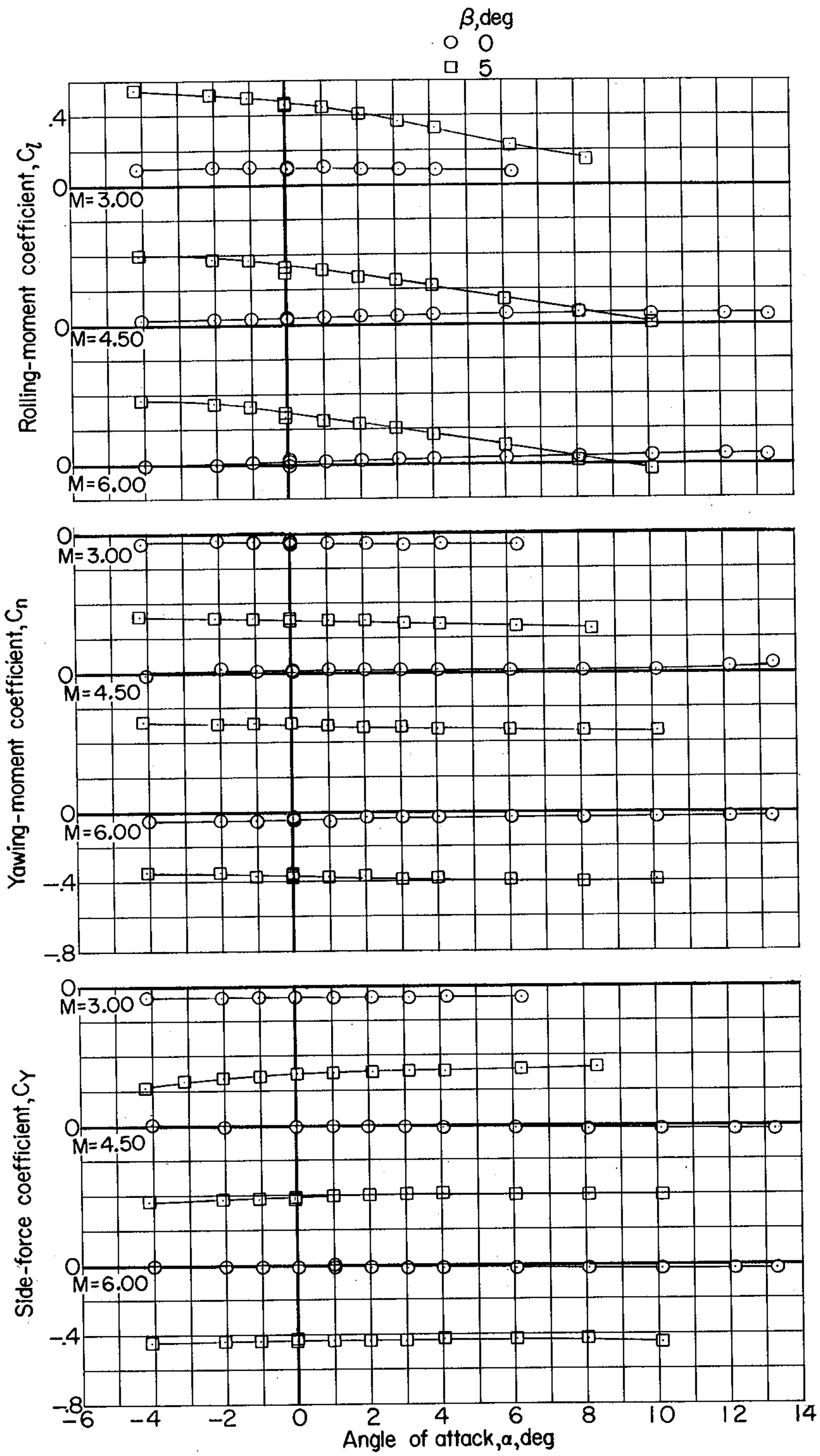

(a) Vertical tails off.

Figure 7.- Lateral directional aerodynamic characteristics of reusable booster without tails and with either single- or double-vertical tails. Shrouds on; $\beta = 0^{\circ}; 5^{\circ}$.

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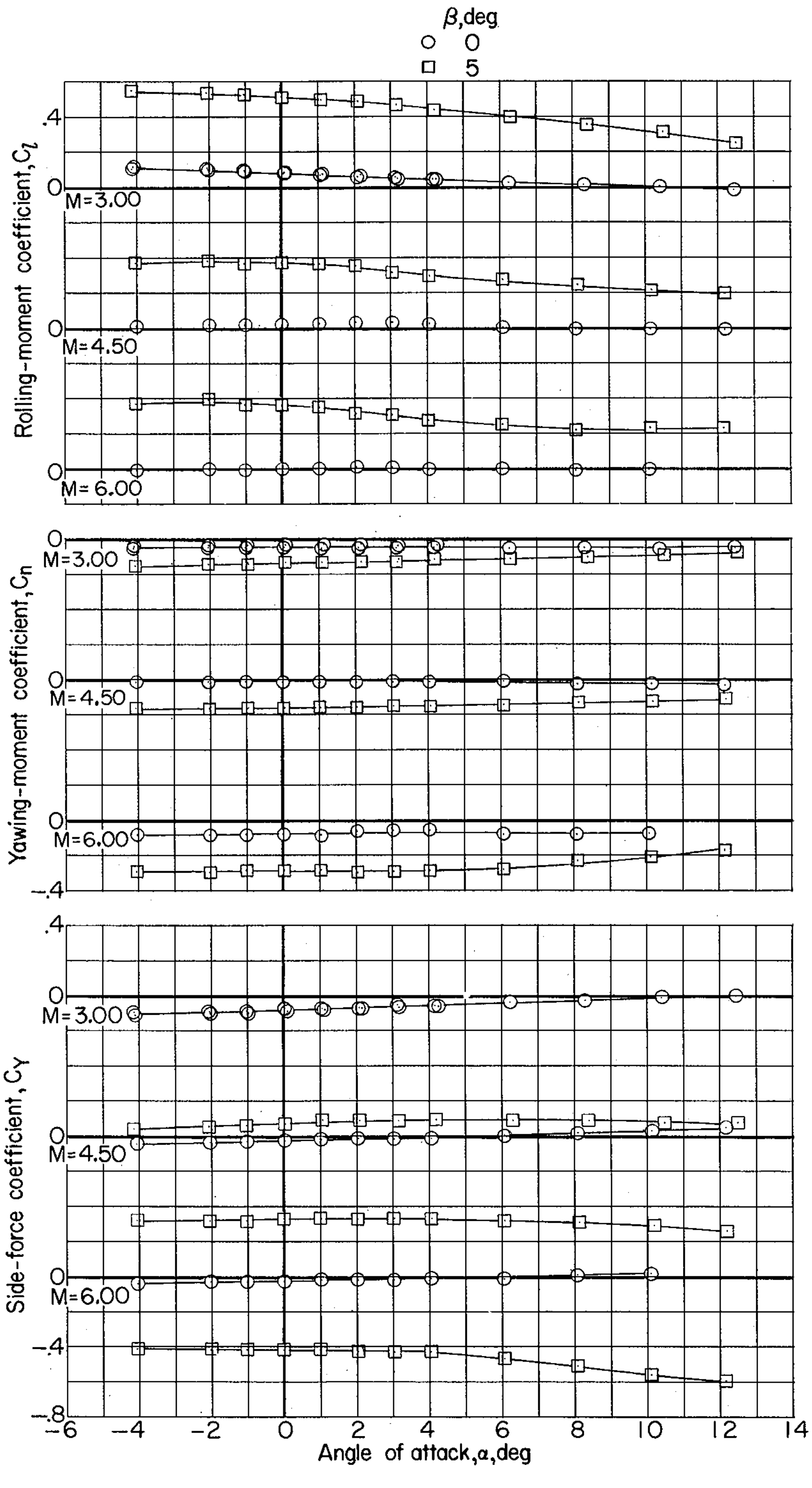
[redacted]



(b) Double-vertical tails.

Figure 7.- Continued.

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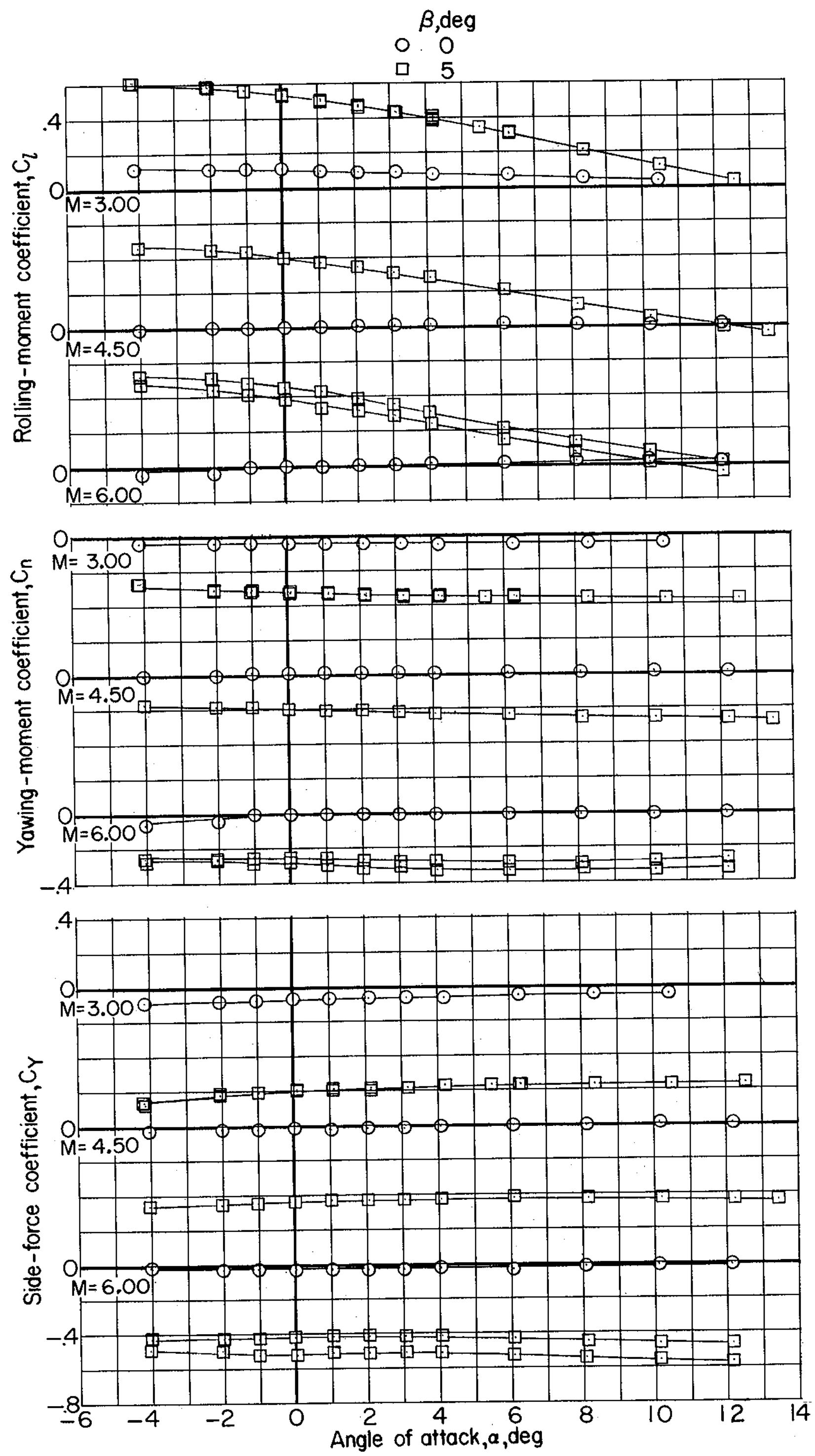

(c) Single-vertical tails.

Figure 7.- Concluded.

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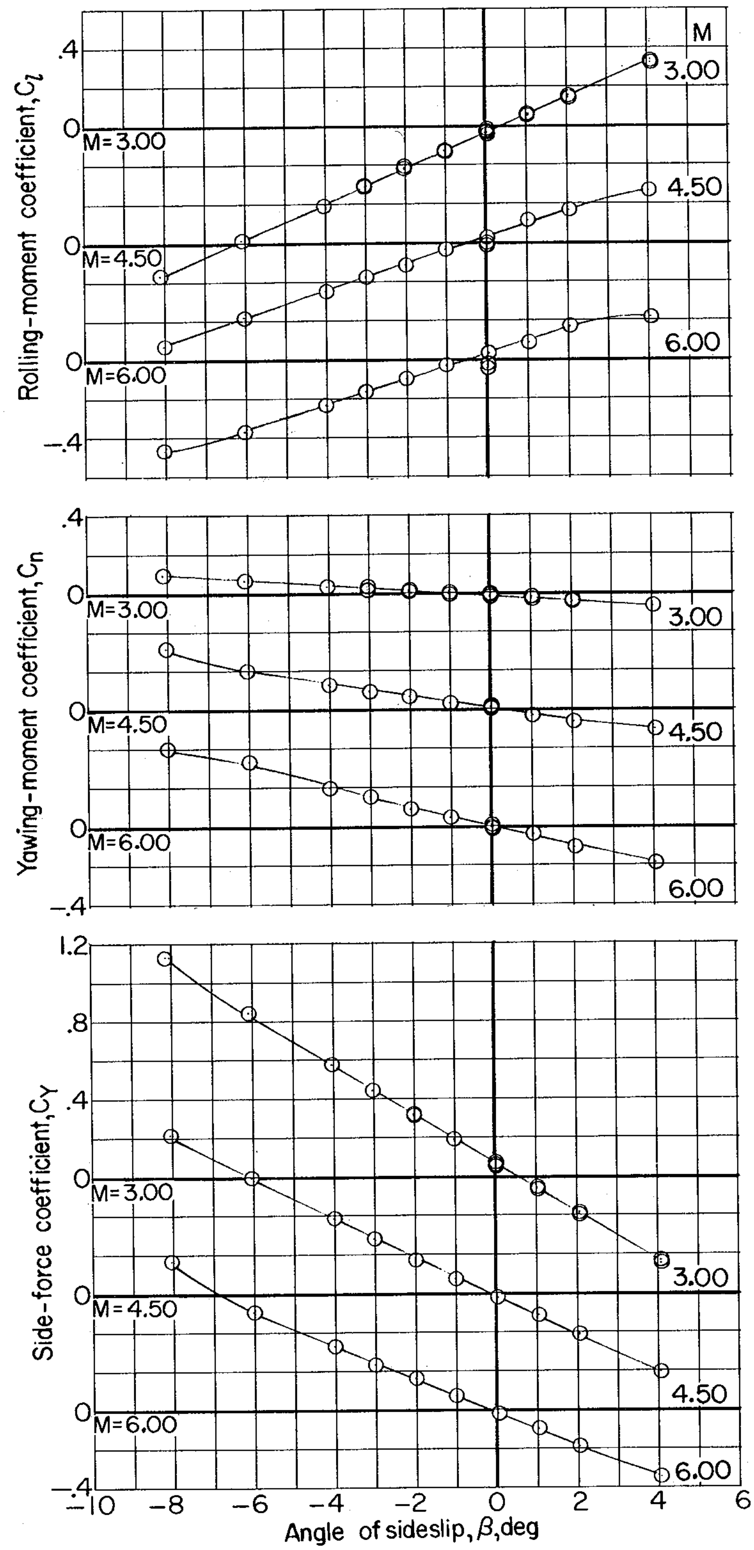

Figure 8.- Variation of lateral directional aerodynamic characteristics of reusable booster with double-vertical tails. Shrouds on; $\alpha = 0^{\circ}$.

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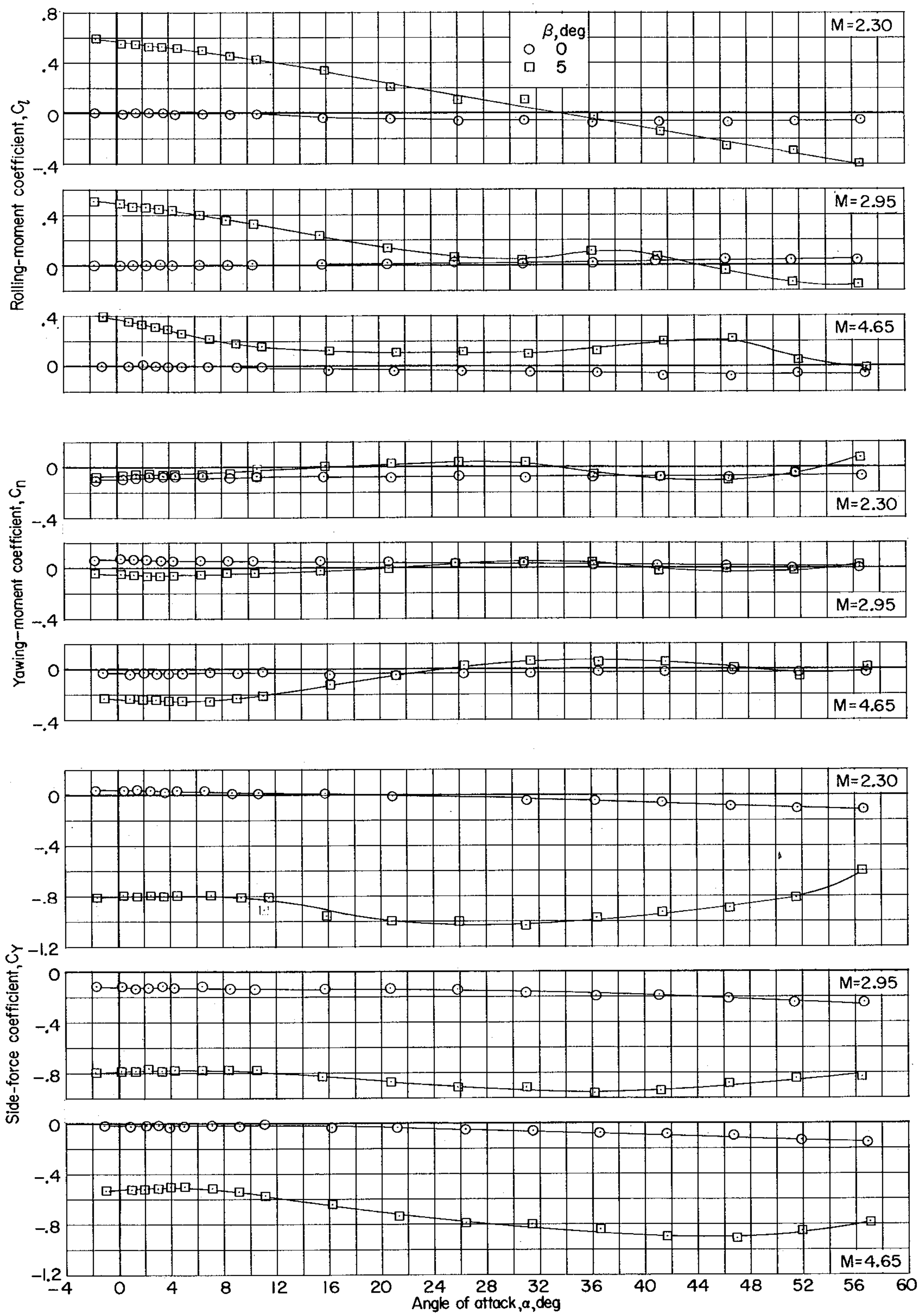

Figure 9.- Lateral directional aerodynamic characteristics at high angles of attack for reusable booster with double-vertical tails. Shrouds on; $\beta = 0^{\circ}; 5^{\circ}$.

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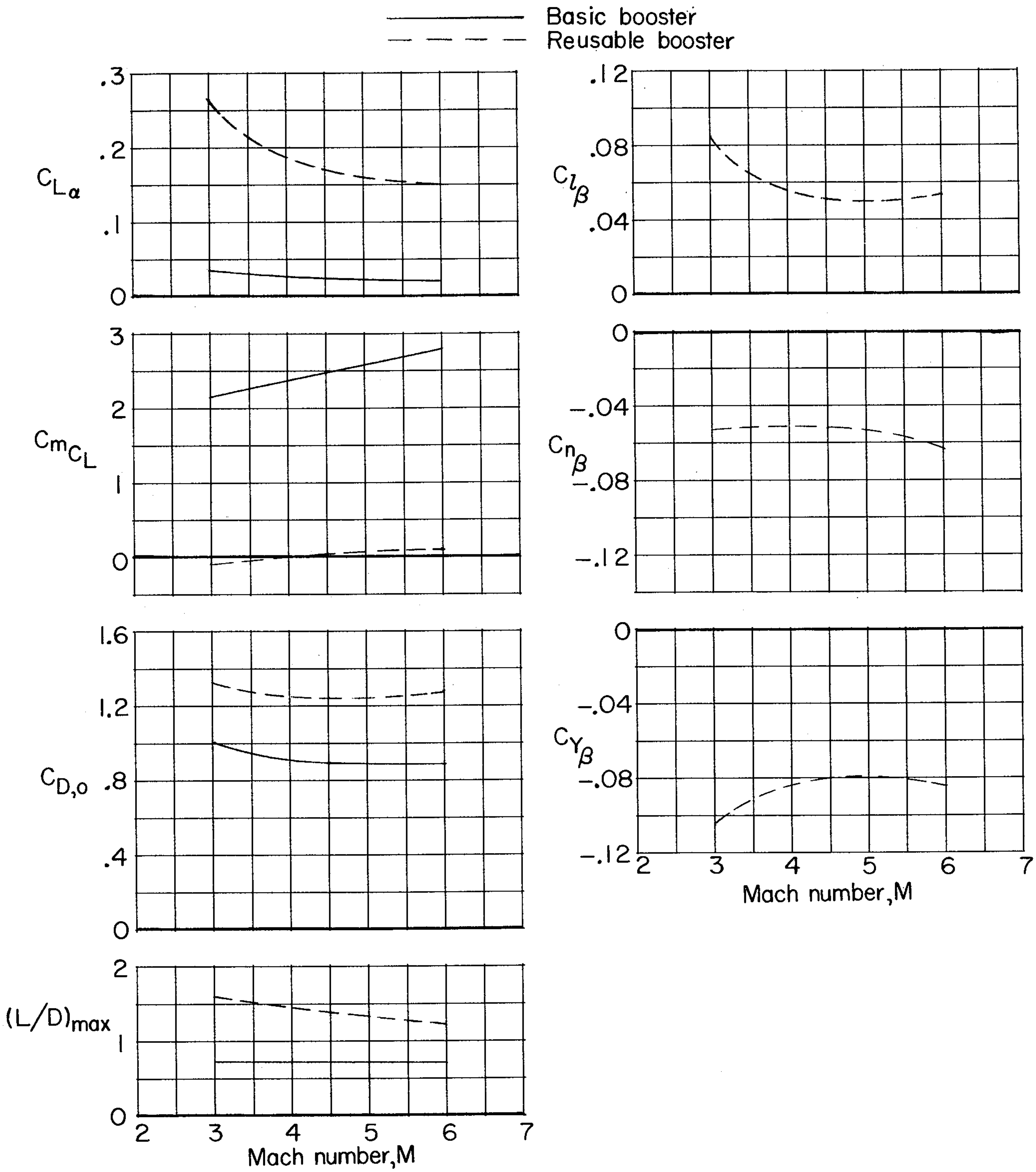

Figure 10.- Summary of the variation of the longitudinal and lateral aerodynamic parameters with Mach number for the basic booster and the reusable booster with single-vertical tails. Shrouds on.

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